Journal of
Civil Engineering and Applications

E-ISSN: 2707-8396
P-ISSN: 2707-8388
www.civilengineeringjournals.com/jcea
JCEA 2025; 6(1): 55-65
Received: 02-12-2024
Accepted: 07-01-2025

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Effect of recycled aggregates on the characteristics of concrete: A review

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DOI: https://doi.org/10.22271/27078388.2025.v6.i1a.39

Abstract

This review explores the influence of recycled aggregates (RAs) on the properties of concrete, focusing on the environmental and mechanical aspects of their integration. Concrete, a vital construction material, is traditionally produced using natural aggregates (NAs), which contribute significantly to resource depletion and environmental degradation. With the rapid consumption of natural resources and the rise of construction and demolition waste, the adoption of RAs, sourced from recycled concrete, has gained attention as a sustainable alternative. Recycled concrete aggregates, however, possess different characteristics compared to NAs, notably higher porosity and water absorption due to adhered mortar. These differences affect the fresh and hardened properties of concrete, often leading to reduced mechanical strength and durability. Despite these challenges, several techniques, such as polymer treatment, mechanical grinding, and thermal treatment, have shown promise in improving the quality of recycled aggregates. Moreover, the incorporation of supplementary cementitious materials, such as fly ash, can further enhance the performance of concrete made with RAs. The review highlights key findings on the effects of RAs on the compressive strength, carbonation resistance, and other durability aspects of concrete, emphasizing the need for tailored mix designs and beneficiation techniques to optimize performance.

Keywords: Recycled aggregates (RAs), concrete properties, sustainable construction

Introduction

Concrete is one of the most extensively used materials in the construction industry, second only to water in terms of global consumption. Studies indicate that the per capita daily usage of concrete worldwide is approximately 8.25 kg (Gagg, 2014) [1]. However, its production has a significant environmental footprint, primarily due to the substantial extraction of natural resources such as sand, gravel, and cement, along with high carbon dioxide emissions during the manufacturing process (Belaid, 2022) [2]. To address these environmental concerns, researchers have proposed the integration of industrial and agricultural waste into concrete as partial replacements for conventional ingredients, offering both ecological and economic advantages (Jagadesh, Ramachandramurthy, & Murugesan, 2022).

Aggregates constitute a major component of concrete, providing structural stability and accounting for 70%-85% of its total volume and roughly 90% of its weight (Nincevic *et al.*, 2019) [4]. According to de Bortoli (2023) [5], approximately 34 billion metric tons of natural aggregates (NAs), including natural fine and coarse aggregates, were extracted in 2016. This figure is expected to reach 62.9 billion metric tons by 2024 (Martinez-Garcia *et al.*, 2021) [6, 10]. The extraction of NAs contributes to several environmental issues, such as habitat destruction, ecosystem degradation, greenhouse gas emissions, increased energy consumption, and air pollution. Furthermore, various stages of aggregate processing—including extraction, transportation, crushing, and screening—add to the cost of construction materials (De Bortoli, 2023) [5].

The physical characteristics of NAs, including shape, size, texture, and composition, significantly influence the properties of fresh concrete. The interaction between aggregate particles and the binding paste determines its overall physical performance (Nincevic *et al.*, 2019) [4].

Construction and demolition waste (CDW) is generated from activities such as new construction, building renovations, and demolitions. It comprises various materials, including concrete, bricks, tiles, glass, plastics, rocks, and soil. Globally, China leads in CDW production with approximately 2,360 million tons annually, followed by the United States with 600 million tons and India with 530 million tons. Within the European Union, France and Germany are the highest contributors, generating around 240 and 225 million tons of CDW, respectively (Wang *et al*., 2021) [7].

The global demand for NAs has been growing at an estimated annual rate of 4%, prompting researchers to explore alternative materials to mitigate environmental degradation (Tang *et al*., 2023) [8]. The total consumption of aggregates is estimated to be around 48.3 billion tons (Wang *et al*., 2021) [7]. One of the most promising substitutes for NAs is recycled materials from construction activities. Currently, the utilization of recycled concrete aggregates (RCAs) surpasses other recycled materials in construction, with several countries establishing guidelines for their use (Bai *et al*., 2020) [9]. Recycling CDW has become a key focus of waste management strategies, emphasizing the need to minimize waste generation, enhance material reuse, and encourage recycling efforts rather than resorting to landfill disposal (Martin-Morales *et al*., 2011) [6, 10].

In recent years, there has been a growing interest in incorporating recycled aggregates (RAs) into concrete as a sustainable alternative to natural aggregates. The construction sector is responsible for consuming nearly 50% of natural resources, producing 50% of total global waste, and utilizing 40% of all energy resources (Okonomou, 2005) [11]. Consequently, the adoption of RAs presents a viable solution for reducing environmental impact while conserving natural resources.

The use of recycled aggregates in high-strength concrete (HSC) has garnered attention due to its potential to minimize environmental impact and decrease reliance on virgin materials. The significance of incorporating RAs in HSC arises from the escalating waste production and the construction sector's urgent need to adopt sustainable practices. Since RAs are primarily derived from CDW, they serve as an effective alternative to NAs in HSC manufacturing, thereby reducing the consumption of newly extracted resources. Studies evaluating the mechanical properties, durability, and environmental advantages of HSC made with RAs have demonstrated promising results.

Recycled aggregates, sourced from the processing and demolition of concrete structures, contribute to environmentally sustainable concrete production. The development of high-performance concrete (HPC) and HSC using RAs aligns with modern sustainable construction goals (Ajdukiewicz & Kliszczewicz, 2002) [12]. Research by Etxeberria *et al*. (2007) [13, 24, 52] found that HSC containing 25% recycled aggregates exhibited improved physical properties. Their study reported a compressive strength ranging between 40 MPa and 70 MPa. Considering the application of HSC in large-scale infrastructure projects such as high-rise buildings, bridges, and offshore structures, the minimum concrete grade typically used is 40 MPa (Gjorv, 2008) [14]. These findings confirm that HSC is characterized by high compressive strength, generally exceeding 40 MPa.

To achieve optimal properties in HSC, researchers recommend using mineral admixtures such as fly ash, lime powder, and ground granulated blast furnace slag. In addition to these supplementary materials, substituting NAs with RAs can contribute to sustainable HSC production without compromising its fresh and hardened properties. However, variations in RA properties depend on their source, the type of parent concrete, and the exposure conditions of the original structures. Figure 1 presents schematic diagrams illustrating the structural differences between conventional concrete with NAs and concrete containing RAs (Behera *et al*., 2014) [15].

Several techniques have been explored to improve the surface characteristics of RCAs, thereby enhancing their mechanical performance and durability. Studies indicate that modified RCAs can achieve compressive strengths of up to 50 MPa (Shayan & Xu, 2003) [16]. The quality and quantity of adhered mortar significantly influence the physical and mechanical properties of RCAs. Since adhered mortar is a porous material, its porosity is primarily dictated by the water-to-binder ratio of the original concrete (Spaeth & Tegguer, 2013) [17]. Various methods have been suggested to reduce the amount of adhered mortar in RCAs, including:

- **Polymer Treatment Process:** Enhances the bonding quality of RCAs and reduces porosity.
- **Mechanical Grinding Process:** Removes weak and porous adhered mortar through mechanical abrasion.
- **Thermal Treatment Process:** Uses heat to break down and remove old mortar, improving aggregate quality.
- **Chemical Treatment Process:** Applies chemical agents to dissolve or weaken adhered mortar, refining aggregate performance.

The fresh and hardened properties of RA-based concrete are significantly affected by the porous nature of RCAs. These characteristics distinguish them from natural coarse aggregates (NCAs) and highlight the need for tailored processing methods to improve their applicability in high-performance concrete production.

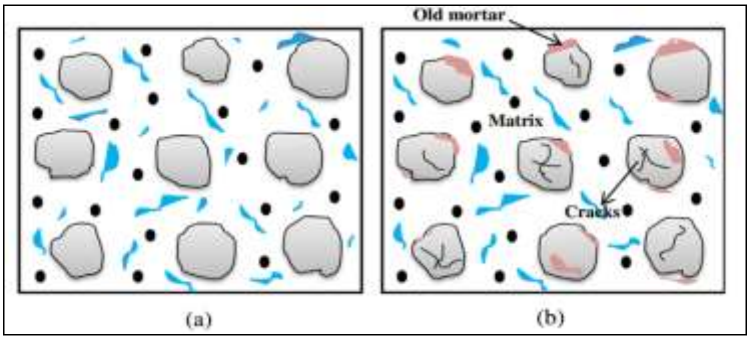

Fig 1: Comparison of matrix structures in (a) natural aggregate (NA) concrete and (b) recycled aggregate (RA) concrete (Behera *et al*., 2014) [15].

The construction industry's rapid growth has led to increased consumption of natural resources and the generation of substantial construction and demolition waste. To address environmental concerns and promote sustainability, the use of recycled aggregates (RAs) in concrete production has gained attention. This review examines the impact of incorporating RAs on the fresh and mechanical properties of Concrete.

Properties of RCA

Adhered mortar and cement paste

Aggregates with particle sizes exceeding 4.75 mm are classified as coarse recycled concrete aggregates (RCA) (Figure 2a), while those with smaller particle sizes are categorized as fine RCA (Figure 2b). Recycled concrete aggregate (RCA) is generally composed of two distinct phases: the natural aggregate (NA) from the original concrete and the adhered mortar (AM) along with the adhered cement paste (ACP) coating the aggregate surface, as illustrated in Figure 2a. Due to the presence of adhered mortar, RCA exhibits higher water absorption, reduced density, lower stiffness, and decreased abrasion resistance compared to NA (de Juan & Gutiérrez, 2009; Kisku *et al*., 2017) [21, 30].

Fig 2: (a) Coarse recycled concrete aggregate (RCA) and AM (b) Fine RCA with ACP

Since the properties of recycled concrete aggregate (RCA) are largely influenced by the amount of adhered mortar (AM) and attached cement paste (ACP), accurately quantifying AM is essential for assessing and regulating RCA quality. Research indicates that smaller RCA particles contain higher amounts of AM due to their increased surface area, which leads to a greater incorporation of old mortar into new concrete (de Juan and Gutiérrez, 2009; Verian *et al*., 2018) [21, 41]. The elevated mortar content results in increased water absorption and reduced dry density of RCA (Etxeberria *et al*., 2007; de Juan and Gutiérrez, 2009) [13, 24, 52, 21], often yielding aggregates with inferior mechanical properties. This occurs because AM typically has lower strength compared to the original parent aggregate. Adverse characteristics of RCA, such as high porosity, excessive water absorption, and reduced stiffness, are more pronounced in fine recycled concrete aggregate (FRCA) than in coarse recycled concrete aggregate (CRCA) due to the higher AM content. As a result, many construction standards impose restrictions on the use of FRCA in structural concrete applications.

The interfacial transition zone (ITZ) between the adhered mortar (AM) and natural aggregate (NA) is a key characteristic of recycled concrete aggregate (RCA). When RCA is incorporated into new concrete, the number of ITZs increases due to the formation of additional interfaces between the AM, the new cement mortar, and the NA (Figure 3). This rise in ITZs enhances the permeability of RCA concrete, allowing aggressive fluids and ions to penetrate more easily, which in turn affects its durability properties (Beushausen *et al*., 2021b) [20].

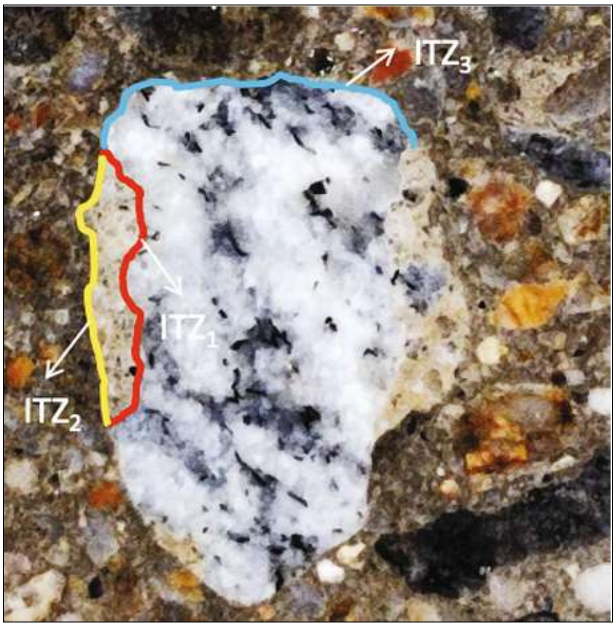

Fig 3: Presence of Multiple Interfacial Transition Zones (ITZs) in Concrete with RCA

Water absorption

The high water absorption capacity of recycled concrete aggregates (RCA) is one of the primary factors limiting their widespread use in concrete production. The porous nature of the adhered mortar (AM) and adhered cement paste (ACP) leads to increased moisture retention, resulting in a greater water demand for concrete incorporating RCA. Typically, the water absorption capacity of natural coarse and fine aggregates falls within the range of 0.5% to 3% and 1% to 5%, respectively. However, coarse RCA (CRCA) can absorb up to 15% of its mass in water, while fine RCA can absorb as much as 20% (Dhir *et al.*, 2019) [22]. This significantly impacts both the fresh and hardened properties of RCA-based concrete.

Given the crucial role of water absorption in determining RCA performance, various enhancement techniques focus on reducing it to improve RCA's suitability for concrete applications. The effectiveness of these treatments is often evaluated by comparing the water absorption values of treated and untreated RCA, as detailed in Table 1.

Table 1: Comparison of Enhancement Techniques for RCA

Treatment Method	Aggregate Type	Feasibility for Large-Scale Use	Working Mechanism	Reduction in Water Absorption (%)	Key Observations	References
Mechanical Abrasion	Coarse, Fine	Yes	Uses friction to remove adhered mortar	Up to 40%	Requires high energy; Needs specialized machinery; Limited efficiency in removing attached mortar	Nagataki *et al.* (2004) [31]
Acid Treatment	Coarse, Fine	Not Suitable	Acid dissolves cementitious residues on RA surfaces	Up to 12%	High water usage; Extended processing time; Handling acid poses risks	Tam *et al.* (2006) [40]
Microwave Treatment	Coarse	Not Suitable	Thermal expansion breaks the bond between mortar and aggregate	Up to 33%	Risk of contamination from sulphates and chlorides; Potential fire hazards with organic impurities	Akbarnezhad *et al.* (2011) [18]
Conventional Heating & Scrubbing	Coarse, Fine	Yes	Uses heat to weaken mortar before mechanical scrubbing	Up to 81%	Requires specialized equipment; High energy consumption	Prajapati *et al.* (2022) [37]
Solar Thermal Treatment	Coarse, Fine	Yes (using solar concentrators like parabolic dishes)	Heat from focused sunlight promotes mortar detachment	Up to 76%	Energy-efficient in sunny regions; Produces high-quality aggregates	Prajapati *et al.* (2021) [36]; Shima *et al.* (2005) [39]
Pozzolanic Slurry Coating	Coarse, Fine	Yes	Fills pores in adhered mortar and strengthens ITZ through additional hydration	Up to 51%	Enhances durability more than mechanical properties; Reduces cement demand in concrete	Kong *et al.* (2010) [27, 60]; Shaban *et al.* (2019) [38]; Wang *et al.* (2013) [42]
Polymer Sealing	Coarse	Not Suitable	Forms a hydrophobic film inside aggregate pores, reducing moisture absorption	Up to 70%	Multiple treatment steps; High cost of polymer materials may limit industrial application	Kou and Poon (2010) [28]; Spaeth and Djerbi Tegguer (2013) [17]
Carbonation Treatment	Coarse, Fine	Yes (conditionally)	CO_2 reacts with $Ca(OH)_2$ in the mortar, forming calcium carbonate to densify the surface	Up to 70%	Enhances ITZ density; May reduce RA pH; Large-scale implementation challenges	Pan *et al.* (2017) [33]; Kou *et al.* (2014) [29]

Dry density

Another key parameter for evaluating the quality of recycled concrete aggregate (RCA) is dry density. Since adhered cement paste (ACP) and adhered mortar (AM) have a lower density than natural aggregates (NA), the dry density of RCA is inherently lower. The higher the AM content, the lower the dry density of RCA.

For coarse RCA (CRCA), the reduction in dry density is relatively minor and does not significantly impact the overall density of concrete. However, fine RCA (FRCA) exhibits a more pronounced decrease in dry density due to the presence of a higher proportion of porous ACP and mortar particles. Studies by Evangelista & de Brito (2007) [23] and Prajapati *et al.* (2021) [36] reported bulk densities of 1235 kg/m^3 and 1305 kg/m^3 for FRCA, reflecting an 18-20% reduction compared to the bulk density of natural fine aggregates used in their research. Furthermore, the presence of a high volume of concrete fines (typically particles smaller than 100-300 µm) can further contribute to a significant decline in FRCA's dry density in some cases.

Mechanical strength of RCA

The mechanical strength of recycled concrete aggregate (RCA) is generally lower than that of natural aggregate (NA) due to the presence of adhered mortar (AM). For example, granite aggregate can exhibit compressive strengths ranging from 150 to 200 MPa, whereas the adhered mortar on these particles may originate from concrete with strengths between 20 and 60 MPa.

When subjected to mechanical stress, the AM tends to detach easily from the NA, leading to a reduction in impact resistance, crushing strength, and abrasion resistance compared to natural aggregates. Table 2 presents a comparison of the physical and mechanical properties of coarse and fine natural aggregates and RCA.

Table 2: Characteristics of Natural and Recycled Concrete Aggregates (Adapted from Prajapati *et al*., 2021[36], and Amadi *et al*., 2022) [19, 45]

Aggregate Type	Dry Density (kg/m^3)	Water Absorption (%)	Compacted Bulk Density (kg/m^3)	Aggregate Crushing Value (%)	Impact Value (%)	Attached Mortar (%)
Natural Granite Aggregate	2740	0.40	1540	21.1	19.2	-
Coarse RCA	2520	5.72	1425	33.8	40.8	29.6
Siliceous River Sand	2610	0.65	1630	-	-	-
Natural Crushed Sand	2450	2.95	1515	-	-	-
Fine RCA	2260	10.75	1305	-	-	-

Impact of Parent Concrete Quality on RCA Characteristics

Research by González-Taboada *et al*. (2016) [25] suggests that the effect of parent concrete quality on RCA properties is not yet fully understood. Padmini *et al*. (2009) [32] investigated CRCA and found that when the strength of parent concrete ranged between 31 and 58 MPa, an increase in strength led to higher water absorption, lower density, and reduced abrasion resistance. This was attributed to the stronger bond between the NA and AM in high-strength parent concrete, resulting in a greater amount of AM remaining attached to the CRCA. In contrast, AM from low-strength parent concrete is more easily detached during crushing and sieving. However, this effect may not be as significant for FRCA since detached AM is usually considered part of the FRCA due to its particle size distribution.

González-Taboada *et al*. (2016) [25] further noted that AM from low-strength parent concrete often has high porosity due to its elevated water-to-cement ratio, potentially leading to lower-quality RCA. Meanwhile, Pedro *et al*. (2014a, b) [34-35] reported that the density of CRCA produced from parent concrete with compressive strengths of 20, 45, and 65 MPa was relatively similar, though water absorption increased as parent concrete strength decreased. Their study also explored the production of concrete made entirely with CRCA and found that, at 28 days, mixes prepared from 65 MPa parent concrete exceeded the design strength due to the high quality of the adhered mortar.

Holmes and Beushausen (2016) [26, 57] demonstrated the influence of parent concrete quality by producing 40 MPa and 50 MPa RCA concrete from 75 MPa parent concrete. Their results indicated that up to 40% replacement with CRCA yielded RCA concrete with compressive strength, tensile strength, elastic modulus, shrinkage, and permeability comparable to NAC. These findings highlight that both the RCA and its adhered mortar properties are directly influenced by the quality of the original parent concrete (Holmes & Beushausen, 2016; Pedro *et al*., 2014a, b) [26, 57, 34-35].

Effect of impurities on RCA

The quality of RCA deteriorates when mixed with materials such as masonry, bricks, ceramics, and aerated concrete (lightweight blocks) from construction and demolition (C&D) waste. These materials introduce impurities, increasing the heterogeneity of RCA. Non-concrete materials, particularly bricks, ceramics, and aerated concrete, possess highly porous microstructures that significantly influence RCA properties. A high concentration of these materials can lead to increased water absorption and reduced dry density.

However, stronger bricks and masonry components tend to exhibit lower absorption rates and higher dry density values. Various standards, including Brazilian NBR-15116 (2005), Portuguese LNEC-E471 (2006), German DAfStb (1998), and Belgian PTV-406 (2003), typically permit a maximum impurity content of 10%. This allowance is considered reasonable, as completely separating concrete waste from mixed C&D waste is often challenging.

Effect of RCA on Fresh and Hardened Properties

Workability

The increased water absorption of recycled concrete aggregate (RCA) leads to a higher water demand in concrete mixtures or necessitates the use of superplasticizers to maintain the required workability of recycled aggregate concrete (RAC). The primary reason for reduced workability in RAC is the presence of porous adhered mortar (AM) and adhered cement paste (ACP), which contribute to an increased water demand in fresh concrete (Kisku *et al*., 2017; Verian *et al*., 2018) [30, 41]. Additionally, the irregular shape, angularity, and rough surface texture of RCA significantly expand the particle surface area and increase inter-particle friction in fresh concrete, requiring either more water or superplasticizer to counteract these effects and achieve the desired workability (Evangelista & de Brito, 2010; Fan *et al*., 2015; Pedro *et al*., 2017) [51, 53, 64].

Research has also demonstrated that the moisture condition of RCA affects the workability of RAC. Poon *et al*. (2004) [66] examined how oven-dry (OD), air-dry (AD), and saturated surface-dry (SSD) conditions of coarse recycled concrete aggregate (CRCA) influence concrete workability. In their study, all concrete mixtures had a constant water-to-cement ratio of 0.57. For the SSD condition, no adjustments were made to the water content. However, for AD and OD conditions, additional water was incorporated into the mix to compensate for the aggregate's absorption capacity. The findings indicated that OD concrete exhibited the highest initial slump, while SSD concrete had the lowest slump across all replacement levels (20%, 50%, and 100%). This variation is attributed to the additional free water present in OD and AD mixtures, temporarily increasing the effective water content in the fresh state. However, the OD concrete mixes experienced the most rapid slump loss over a 165-minute period due to the high absorption capacity of OD aggregates, whereas SSD mixes retained their slump more effectively throughout the same duration.

Similarly, Ferreira *et al*. (2011) [54] investigated the effects of pre-saturation and water compensation techniques on CRCA. Their study revealed that the targeted slump was achieved in all concrete mixtures containing CRCA at 20%, 50%, and 100% replacement levels. However, a notable reduction in compressive strength was observed in pre-saturated mixes, particularly at a 20% RCA replacement level. This reduction was attributed to increased bleeding observed during compaction, which led to a higher effective water content in the cement paste (Poon *et al*., 2004) [66]. Excessive bleeding is undesirable as it creates voids within the hardened concrete after the surplus water is absorbed by the binder matrix. Additionally, the pre-saturation approach poses challenges for field applications due to difficulties in maintaining a consistent SSD condition, especially for fine recycled concrete aggregate (FRCA).

Moreover, the use of superplasticizers can enhance the workability of RAC while reducing water demand by approximately 15 to 30% (Cartuxo *et al*., 2015) [49]. However, research indicates that the efficiency of superplasticizers declines as the RCA replacement level increases, especially in the case of fine recycled concrete aggregate (FRCA). Consequently, a higher dosage of superplasticizer may be necessary to achieve the desired workability when incorporating greater amounts of RCA into the concrete mix.

Compressive strength

Replacing natural aggregate (NA) with recycled concrete aggregate (RCA) can significantly influence the strength properties of concrete. Generally, an increase in RCA content tends to reduce concrete strength (Kisku *et al*., 2017) [30]. This reduction is primarily attributed to the presence of less rigid and more porous adhered mortar (AM), which weakens the aggregate matrix (Pedro *et al*., 2017) [64]. Additionally, the crushing and demolition processes can introduce microcracks in RCA, which act as defects or weak zones in the concrete structure (Kisku *et al*., 2017; Pepe *et al*., 2016) [30, 65]. Research indicates that due to the higher adhered cement paste (ACP) content in fine recycled concrete aggregate (FRCA), the reduction in strength is more pronounced in fine aggregate-based recycled concrete (FRAC) compared to coarse aggregate-based recycled concrete (CRAC) (Pepe *et al*., 2016; Verian *et al*., 2018) [65, 41]. However, the extent of strength reduction largely depends on the level of RCA replacement.

To compare beneficiation methods, studies have examined the effects of thermo-mechanical treatment and cement-slurry coating on RAC. Typically, the reduction in 28-day compressive strength is minimal when RCA replacement is below 50%, but at 100% substitution, strength losses can reach up to 33%. Beneficiation techniques, such as the removal or enhancement of AM, help mitigate this strength loss and reduce variability in compressive strength. For instance, ongoing research at IIT Madras has shown that using thermo-mechanically treated RCA at 100% replacement does not significantly impact strength. This improvement is attributed to the substantial removal of AM and ACP, leading to better aggregate properties. Similarly, cement-coated RCA demonstrated enhanced aggregate characteristics, although the increase in compressive strength was moderate—about 15% higher than untreated CRAC.

On the other hand, pre-soaking RCA in water to address its high absorption capacity may negatively affect the compressive strength of recycled aggregate concrete (Etxeberria *et al*., 2007; Poon *et al*., 2004) [13, 24, 52]. This occurs due to excessive bleeding in pre-saturated mixes during compaction, which raises the effective water content in the cement paste (Poon *et al*., 2004) [66]. To counteract this issue, Etxeberria *et al*. (2007) [13, 24, 52] suggest maintaining an RCA saturation level of approximately 80%, although achieving consistent control under field conditions may be challenging. Alternatively, Poon *et al*. (2004) [66] recommend using air-dried RCA with adjusted water compensation for concrete production.

Despite its high absorption and desorption capabilities, RCA can sometimes benefit concrete performance. Studies by Dimitriou *et al*. (2018) [50] indicate that the absorbed water in RCA can gradually release from AM pores, serving as internal curing water. This internal curing process aids hydration, reducing autogenous shrinkage in low water-to-binder (w/b) ratio concretes. Their research found that concrete with 100% CRCA exhibited a faster strength gain rate over 56 days at a w/b ratio of 0.25 compared to control NAC (Dimitriou *et al*., 2018) [50]. Furthermore, AM may contain unhydrated cement particles, which can enhance nucleation sites, promote additional hydration product formation, and strengthen the cement-aggregate interface in concrete (Rakhimova & Rakhimov, 2015; Ren *et al*., 2020). This observation aligns with findings by Pedro *et al*. (2017) [64], who reported that the gap in compressive strength between NAC and RAC (both fine and coarse) gradually decreased over a 56-day period.

Research has shown that the quality of RCA plays a crucial role in determining the strength properties of RAC. Holmes and Beushausen (2016) [26, 57] suggest that RCA derived from high-strength concrete and free from contaminants should be used to produce structural concrete with comparable or slightly lower strength. Their study found that coarse RCA sourced from 75 MPa parent concrete could successfully produce 40 MPa and 50 MPa concrete with strength levels similar to NAC, provided the RCA replacement did not exceed 40%. Similar findings were reported by Pedro *et al*. (2014a, b) [34-35], who demonstrated that 100% coarse RCA from 65 MPa parent concrete could be utilized to achieve concrete of the same strength (65 MPa). Conversely, concrete made with RCA from 20 MPa and 45 MPa parent concrete failed to meet their respective 28-day design strengths, primarily due to the inferior quality of RCA and the presence of adhered mortar.

In another study, Amadi *et al*. (2022) [19, 45] investigated the use of fine RCA from 55 MPa parent concrete, replacing up to 50% of fine natural aggregate. The fine RCA was incorporated in an air-dry state, and for concrete mixes with water-to-binder (w/b) ratios of 0.45 and 0.55, the 28-day compressive strength of all FRAC mixes was found to be comparable to the control NAC. When supplementary cementitious materials (SCMs) were introduced, the difference in long-term strength gain between NAC and RA concrete became more evident. For instance, Kou *et al*. (2007) [62] observed an 8% strength increase in NAC over a 90-day period, while coarse RCA concrete with fly ash exhibited a 14-48% strength improvement. Similar trends were noted by Kou *et al*. (2011) [61], Wang *et al*. (2013) [42], and Ann *et al*. (2008) [46]. The study by Kou *et al*. (2007) [62]

indicated that the optimal strength was achieved when 25% of cement was replaced with fly ash. At 28 days, concrete mixes containing fly ash showed slightly lower compressive strength than their counterparts without fly ash, regardless of the RCA replacement level (0, 20, 50, and 100%). However, by 90 days, all fly ash mixes exhibited higher compressive strength compared to their non-fly ash equivalents.

A similar pattern was observed by Amadi *et al*. (2022) [19, 45] for FRAC mixes with 0.45 and 0.55 w/b ratios, incorporating 25% and 50% fine RCA and 30% fly ash replacement for cement. At 3 days, the compressive strength of these mixes was 22-44% lower than the control concrete, but by 180 days, all FRAC mixes exhibited up to a 14% higher strength than the reference concrete. This improvement is attributed to the continued pozzolanic reactions in fly ash concrete. It is well established that SCMs, such as fly ash, provide long-term benefits in RAC, though they require extended curing durations for optimal performance.

Effect of RCA on Durability Properties

Durability refers to a material's capacity to withstand both chemical and physical degradation over an extended period within a specific environment. Unlike inherent properties, durability must be evaluated concerning the conditions in which the material is used (Alexander & Beushausen, 2019) [43]. Concrete deterioration occurs when external elements such as ions, liquids, and gases—collectively known as fluids—penetrate its pore structure through mechanisms such as permeation, diffusion, absorption, migration, and convection (Beushausen *et al*., 2021b) [20]. The extent of fluid infiltration is primarily governed by factors like porosity, the connectivity of pores, and the permeability of the cement paste and interfacial transition zone (ITZ), particularly in cases where multiple ITZs overlap (Beushausen *et al*., 2021b) [20].

In the case of recycled aggregate concrete (RAC), durability is influenced not only by external conditions but also by internal factors such as the quantity of adhered mortar (AM) and adhered cement paste (ACP), the presence of concrete fines, and the complexity of multiple ITZs. Furthermore, the irregular shape, rough texture, and angularity of recycled concrete aggregates (RCA) contribute to increased water demand, which in turn affects penetrability and overall durability (Fan *et al*., 2015; Pedro *et al*., 2017) [53, 64]. The surface texture of RCA exhibits a strong fractal nature, leading to increased complexity in the concrete matrix (Hilal, 2016) [56]. However, these adverse effects are more pronounced when RCA replacement levels exceed 50%.

According to Amadi *et al*. (2022) [19, 45], one of the key challenges in RAC durability is the absence of standardized design methods to enhance the quality of RCA and RAC. Important considerations for improving RAC performance include selecting appropriate RCA sources (Holmes & Beushausen, 2016) [26, 57], optimizing the crushing process (Fan *et al*., 2015) [53], managing RCA moisture content (Poon *et al*., 2004) [66], refining the mixing approach, implementing suitable curing regimes (Amadi *et al*., 2022) [19, 45], and incorporating supplementary cementitious materials (Amadi *et al*., 2022; Kong *et al*., 2010; Wang *et al*., 2013) [19, 45, 27, 60, 42].

Despite these challenges, advancements in performance-based approaches for RAC have been made, alongside the development of durability specifications and test methods to assess RAC's long-term performance. These improvements can support the adoption of RCA in construction by establishing clear acceptance criteria and performance standards. This section explores the durability of RAC, focusing on mechanisms of deterioration, fluid transport properties, chloride ingress, and carbonation.

Fluid-flow properties

Water absorption in concrete is a crucial parameter as it reflects the ease with which moisture and harmful fluids can infiltrate the material, potentially leading to degradation. Typically, moisture enters the pores of unsaturated concrete due to capillary action (absorption), whereas in saturated concrete, water can infiltrate under externally applied pressure (permeation). Since both processes involve filling the pore structure with water, there is a direct correlation between water absorption and concrete porosity (Kelham, 1988; Ballim, 1993; Moore *et al*., 2021; Beushausen *et al*., 2021b) [59, 20, 47]. As a result, water absorption serves as a key indicator of porosity and, consequently, the durability of concrete, especially when considering recycled aggregate concrete (RAC).

RAC generally exhibits higher water absorption compared to natural aggregate concrete (NAC), primarily due to the porous nature of adhered cement paste (ACP) in recycled concrete aggregates (RCA). Additionally, the extra water required in RAC mixtures to maintain workability equivalent to NAC can contribute to increased porosity and permeability (Evangelista & de Brito, 2010; Soares *et al*., 2014) [51]. Studies indicate that as the proportion of RCA in concrete increases, the pore volume expands, leading to higher water absorption (Pedro *et al*., 2017) [64].

Research by Pedro *et al*. (2017) [64] found that the water absorption by immersion in concrete made entirely with coarse RCA was 22% and 37% higher than NAC for laboratory-produced RCA (RAC-LC) and RCA derived from construction and demolition waste (RAC-RW), respectively. Similarly, for fully fine RCA concrete, water absorption in RAC-LC and RAC-RW was 33% and 43% greater than that of NAC. These findings highlight that fine RCA concrete tends to have higher water absorption than its coarse counterpart. Moreover, the study demonstrated that the quality of RCA significantly affects the final concrete properties, with laboratory-produced RCA yielding superior results compared to C&D waste-derived RCA. These observations align with the findings of Matias *et al*. (2014) [63] and Soares *et al*. (2014), who reported that water absorption in 100% coarse RCA concrete (CRAC) increased by 28% and 21%, respectively, compared to NAC. In contrast, Evangelista and de Brito (2010) [51] found that water absorption in 100% fine RCA concrete (FRAC) was 46% higher than NAC.

Regarding capillary water absorption, studies by Soares *et al*. (2014) and Pedro *et al*. (2017) [64] revealed that the sorptivity, or rate of capillary absorption, increased by up to 42% and 59%, respectively, in concrete composed entirely of CRCA. In the case of fully fine RCA concrete, sorptivity increased by 70% (Evangelista & de Brito, 2010) [51] and 119% (Pedro *et al*., 2017) [64] relative to NAC. The elevated sorptivity in FRCA concrete is likely due to several factors, including the greater porosity of fine RCA, the increased water content in FRCA mixtures, and the presence of a significant number of small-diameter capillaries. The size distribution of these capillaries plays a critical role, as smaller capillary diameters generate higher capillary pressures, further influencing water absorption (Evangelista & de Brito, 2010) [51].

Chloride Attack

The ability of concrete to resist chloride ion penetration is a crucial durability factor, as chloride ingress can initiate the corrosion of reinforcing steel. The deterioration process occurs when chloride ions from de-icing salts or marine environments diffuse through the concrete's pore structure. This diffusion reduces the solubility of calcium hydroxide ($Ca(OH)_2$), alters the electrochemical environment around the steel reinforcement, and lowers the pH of the pore solution, ultimately leading to the de-passivation of the steel. Additionally, chloride salts are hygroscopic, increasing the moisture content within the concrete (Hunkeler, 2005) [58]. While some chlorides can be chemically bound within hydrated cementitious materials, they may later be released due to processes like carbonation. This release results in the presence of free chloride ions, which, when exceeding a critical threshold, contribute to steel corrosion (Alexander *et al*., 2012; Hunkeler, 2005) [44, 58].

Compared to conventional natural aggregate concrete (NAC) of similar strength, recycled aggregate concrete (RAC) generally exhibits lower resistance to chloride ion penetration (Guo *et al*., 2018) [55]. The porous nature of adhered cement paste (ACP), the interconnected pore network, microcracks, and the presence of multiple interfacial transition zones (ITZs) in recycled concrete aggregate (RCA) contribute to increased chloride ion permeability in RAC. Studies have reported reductions in chloride resistance ranging from 14% to 34% for fully fine RCA (FRCA) concrete compared to NAC (Evangelista & de Brito, 2010; Pedro *et al*., 2017) [51, 64]. Conversely, concrete made entirely with coarse RCA (CRCA) demonstrated chloride resistance comparable to NAC (Matias *et al*., 2014; Pedro *et al*., 2017) [63, 64]. This suggests that the higher ACP content and additional water required for workability in FRCA concrete negatively impact its durability.

Amadi *et al*. (2022) [19, 45] examined the chloride penetration resistance of fine RCA concrete using multiple testing methods, including electrical resistivity measurements such as surface electrical resistivity (SER) and chloride conductivity index (CCI) tests, alongside a bulk diffusion test to assess chloride transport mechanisms. The study investigated two concrete series with water-to-binder (w/b) ratios of 0.55 and 0.45, labelled as Series A and B, respectively. Fine RCA was incorporated at replacement levels of 25% and 50%. The findings revealed that, regardless of the w/b ratio and testing age (28 and 180 days), the inclusion of up to 50% fine RCA did not significantly affect the electrical conductivity of the concrete.

Carbonation

Carbonation is a significant factor in reinforced concrete durability, as it is one of the primary mechanisms, along with chloride ingress, that can contribute to the corrosion of reinforcing steel. During carbonation, the pH of the concrete pore solution decreases from approximately 12.5 to around 8.5 in fully carbonated concrete, reducing the protective passivation layer around the steel and potentially initiating corrosion.

Several factors influence carbonation, including relative humidity, temperature, CO_2 concentration, curing conditions, age of the concrete, binder composition, and binder content (Beushausen *et al*., 2021b; Mackechnie & Alexander, 2002; Salvoldi *et al*., 2015) [20]. To compare different concretes, the relative carbonation depth—defined as the ratio of the carbonation depth of recycled aggregate concrete (RAC) to that of natural aggregate concrete (NAC) under identical conditions—is commonly used. A ratio greater than 1 indicates that NAC has superior carbonation resistance compared to RAC.

Research by Kou and Poon (2012) demonstrated a decline in carbonation resistance in concrete containing coarse recycled concrete aggregate (RCA). As the replacement level of coarse RCA increased from 20% to 100%, the relative carbonation depth reached approximately 1.4 at 28 days and 1.2 at 90 days. Similarly, Evangelista & de Brito (2010) [51] observed a comparable trend in fine RCA concrete at 30% and 100% replacement levels. Their study found that at 100% fine RCA content, the relative carbonation depth varied between 0.9 and 1.7 after CO_2 exposure for 7, 14, 21, and 91 days. A statistical analysis of previous studies by Silva *et al*. (2015) indicated that at 100% replacement levels, relative carbonation values could reach up to 2.15 for coarse RCA and 6.03 for fine RCA, with greater variability observed in fine RCA mixes. The higher carbonation depth in RCA concrete is primarily due to the porous nature of adhered cement paste (ACP), which increases its permeability.

The use of supplementary cementitious materials (SCMs) can further reduce carbonation resistance in RAC. Kou and Poon found that increasing the fly ash replacement for cement from 25% to 35% lowered the carbonation resistance in concrete containing 20%-100% coarse RCA. In mixes with 25% fly ash, the maximum relative carbonation depth was 1.8 at 28 days and 1.5 at 90 days. When fly ash content increased to 35%, the values rose to 2.3 and 1.7, respectively. Similar findings were reported by Sim & Park (2011), who studied mixed RCA concrete with 15% and 30% fly ash replacement, incorporating fully coarse RCA and varying fine RCA levels (0%, 30%, 60%, and 100%). The reduction in carbonation resistance is attributed to the depletion of carbonatable material, such as calcium hydroxide ($Ca(OH)_2$), which is consumed in pozzolanic reactions and reduced due to cement replacement by fly ash (Mackechnie & Alexander).

It is important to note that carbonation does not always compromise structural durability. In many reinforced concrete applications, particularly in indoor or dry outdoor environments, carbonation does not necessarily lead to steel corrosion. Additionally, unreinforced concrete elements such as bricks and blocks may benefit from carbonation, as they can act as a carbon sink, helping to capture environmental CO_2.

Conclusion

Numerous studies have examined the performance of concrete incorporating recycled concrete aggregate (RCA) at varying replacement levels. The general consensus is that adjustments in mixture proportioning are essential to achieve comparable performance with natural aggregate concrete (NAC). The potential decline in the mechanical and durability properties of RCA-based concrete can, however, be mitigated through various strategies, including aggregate treatment and beneficiation techniques.

Significant advancements have been made in RCA beneficiation methods, which help preserve aggregate properties and, in turn, minimize their impact on concrete strength and durability. When incorporating RCA into concrete, it is crucial to leverage a thorough understanding of its characteristics to optimize mix design and counteract any negative effects. Researchers employ different testing methods to evaluate RCA's impact on durability, but these assessments can sometimes be influenced by the specific theories they aim to validate. Therefore, ensuring a proper understanding and careful interpretation of performance testing methods is essential for reliable evaluations of RCA-based concrete.

Additionally, durability indicator tests should be used judiciously to assess the long-term behavior of RCA concrete. The adoption of performance-based specifications can further guide the design of RCA concrete mixes, ensuring they meet the required engineering properties. By tailoring RCA concrete to achieve strength and durability comparable to conventional concrete, it becomes more viable for widespread use in infrastructure projects, promoting sustainable construction practices while maintaining structural integrity.

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